THE LAMB WAVE INSPECTION OF CHEMICAL PLANT PIPEWORK

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INTRODUCTION

Corrosion in pipework is a major problem, particularly in the oil, gas, chemical and petro-chemical industries. Since a high proportion of industrial pipelines are insulated, this means that even external corrosion cannot readily be detected without the removal of the insulation, which in most cases is prohibitively expensive. There is therefore an urgent need for the development of a quick, reliable method for the detection of corrosion under insulation (CUI).

The use of cylindrical Lamb waves propagating along the pipe wall is potentially a very attractive solution to this problem since they can propagate a long distance under insulation and may be excited and received using transducers positioned at a location where a small section of insulation has been removed. There has been a considerable amount of work on the use of Lamb waves for the inspection of pipes and tubes, most of which has been on small (typically 1 inch) diameter heat exchanger tubing (see, for example, [1-4]).

The authors are working on a project whose ultimate aim is to develop a guided wave testing technique for the inspection of pipework in chemical plants, the original target being to detect any areas of corrosion larger than 3T x 3T in area and T/2 deep where T is the pipe wall thickness. Quantitative defect detection studies [5] showed that the reflection from a notch-like defect is approximately linearly related to the proportion of the circumference of the pipe covered by the notch and is also a function of the notch depth expressed as a fraction of the wall thickness. Therefore the reflection coefficient from a defect half the wall thickness deep covering a given fraction of the circumference will be the same in any pipe size. If the wall thickness were proportional to the pipe diameter (i.e. constant diameter/thickness ratio), this would imply that if a defect 3T x 3T in area and T/2 deep could be detected in one pipe size then it could be detected in any other size. Unfortunately, however, the wall thickness of typical chemical plant pipes only increases slowly with diameter. For example, a 3 inch diameter schedule 40 pipe has a wall thickness of 5.5 mm while in a 6 inch pipe the wall thickness is only increased to 6.9 mm. This means that as the pipe diameter increases, the reflection coefficient from a 3T x 3T x T/2 defect decreases. Subsequent discussions with the industrial partners have led to the conclusion that the target can be relaxed to the detection of defects T/2 deep covering 16% of the circumference (a circumferential extent of half the pipe diameter, D/2). The technique is to work on insulated pipe in the 2 -12 inch (51 - 305 mm) nominal bore diameter range and an inspection range allowing successive transducer positions to be at least 15m apart is required. (While most of the test work has been on pipes in the 2-12 inch diameter range, the technique is not limited to these sizes.)

The L(0,2) mode (the terminology used to describe cylindrical Lamb modes is discussed in [1]) in the frequency range around 70 kHz is very attractive to use for long range testing [5-7] since it is practically non-dispersive and is also the fastest mode, which means that it will be the first signal to arrive at the receiver and so can readily be separated by time domain gating. Its mode shape is similar to that of the s_0 mode in plates at low frequency-thickness products, the particle motion being predominantly axial and the strain being roughly uniform through the pipe wall. It is therefore well suited to the detection of corrosion which may initiate at either surface of the pipe.

Alleyne and Cawley [6] reported the development of a dry coupled piezoelectric transducer system for the excitation of the axially symmetric L(0,m) modes in pipes. It comprises a ring of length-expander piezoelectric elements which are clamped individually to the pipe surface. Each element is faced with a thin brass or steel shim to protect it from wear and is backed with tungsten loaded epoxy contained in a tufnol housing. The completed unit is coupled to the pipe by pressing down on the top of the tufnol housing. The number of elements in the ring should be greater than n where F(n,1) is the highest order flexural mode whose cut off frequency is within the bandwidth of the excitation signal. In the site tests carried out to date, rings of 16 elements were used on 3 inch pipes, while 32 element rings were employed on 6 and 8 inch pipes.

Initial site trials of the technique have been reported previously [7]. Propagation distances of approaching 50 m were obtained and by using two rings of transducers it was shown to be possible to obtain uni-directional propagation. Further development work on the excitation and reception system has since been carried out, resulting in typical signal to noise ratios of better than 40 dB on site and approaching 50 dB in the laboratory. The reflection coefficient from a notch T/2 deep covering 16% of the pipe circumference is approximately 0.05 (-25 dB) so this signal to noise ratio should be adequate. (Previous work [5] has shown that the reflections from notches and troughs of the same maximum depth are similar provided that the axial extent of the trough is significantly less than the wavelength of around 80 mm.) This paper reports the first set of "blind" trials carried out on an insulated pipe which was suspected to be defective.

TEST PROCEDURE

One of the operating companies supporting this work was planning to replace insulation along an 8 inch schedule 30 (7 mm wall thickness) atmospheric residue line in a pipe track from a refinery. The insulation comprised 50 mm thick mineral wool loosely wrapped round the pipe and covered with galvanised steel sheeting. Problem areas associated with loose fitting insulation at some points along the lines in this pipe track had been identified in the past, with repairs being made to the pipeline. The company had decided to remove all the insulation and to inspect the line visually prior to re-commissioning. This provided an ideal opportunity to test the Lamb wave technique in the field and also to gain invaluable experience on real corrosion defects. The Lamb wave tests could be conducted before the insulation was removed and then the results obtained correlated with the visual inspection.

The overall length of the line inspected using the Lamb wave technique was 550 m and contractors removed 1m lengths of insulation at intervals of at least 20m along the line in order to provide access for transducer placement. The pipe was supported at regular intervals of about 8 m and these pipe supports provided useful reference points. The majority of the supports were essentially steel 'Tee' brackets welded to the pipe. Each bracket was about 450mm long, 70mm high and 10mm thick and was welded to the pipe along its length on both sides so that it was normal to the pipe surface and in-line with the pipe axis. A few pipe supports were of a 'U' shape yoke design. The dimensions were similar to the 'Tee' design, but the support was welded over about half of the pipe circumference.

In previous site trials [7] the data had been collected and then analysed at leisure on completion of the trials. However, it was agreed for this exercise that a methodology more in keeping with standard site practice would be adopted, an immediate assessment of the time domain signals collected at each test location being made. Suspect areas were then marked on the line so that the insulation at these points could be removed for immediate visual inspection. More detailed analysis of the signals was conducted after the trials were completed. At the end of the trials, all the insulation along the line was removed and the entire length of the pipe was inspected visually in order to determine whether any significant areas of corrosion had not been detected.

In all the tests the excitation signal was a 5 cycle tone burst modified by the application of a Hanning window function, most tests being carried out at a centre frequency of 64 kHz. Up to 128 successive signals were averaged to improve the signal-to-noise ratio and increase the accuracy of the measurements. Prior to each test, any loose corrosion products were removed from the pipe at the transducer position and careful measurements were taken of the positions of all visible features (mainly pipe supports); the transducer rings were then located and clamped down, ensuring that the load on each transducer was applied evenly. More details of the instrumentation and transducer clamping arrangement are given in [7]. The set-up time would be reduced dramatically by the use of a pneumatic clamping arrangement and this is now being developed. All the tests were carried out with the instrumentation in the back of a four wheel drive vehicle, the power being provided by a small diesel generator.

RESULTS

The transducers were positioned at 13 test locations along the pipeline. At each location tests were carried out with the L(0,2) mode being excited in the forward and backward directions in turn [7]. Figs 1a and 1b show the signals obtained by sending waves in the forward and backward directions respectively at one test location. The time axis has been converted to a distance scale using the velocity of the L(0,2) mode obtained from the theoretical dispersion curves. There is a 'dead zone' of about 1m at the start of the traces due to the operation of the rudimentary diode bridge circuit which was connected between the ring and the function generator and capture unit to isolate the receiver amplifier from the large amplitude excitation signals. The length of the 'dead zone' could be reduced by improving the circuit design.

The first large signal marked Y on Fig 1a is due to a welded yoke pipe support (support number PS64) and this is closely followed by a reflection (W) from a butt weld. The three remaining significant echoes correspond to two further welded yoke supports (Y) with a weld (W) roughly midway between them. The weld signals were identified at the time of the test and this was confirmed when the insulation was removed. Propagation in the backward direction (Fig 1b) revealed three welds; in this case the reflections from the pipe supports were smaller than those in the forward direction. This is because they were welded 'Tee' rather than yoke supports.

Figs 2a and 2b show the signals received in tests in the forward and backward directions respectively at an adjacent test location. The first signal in Fig 2a is from a weld and this is followed by a group of echoes coming from the region of support PS60. This was identified as a corrosion site and when the insulation was removed, a region of corrosion having a maximum depth of about 2 mm (29% of the wall thickness) extending over about 25% of the pipe circumference and 400 mm along the pipe was seen. There was no significant echo from the region of the next pipe support, and no corrosion was subsequently seen at this location. The two remaining relatively large echoes in the trace are from welds. The small echo at a range of 35 m is from the welded yoke support PS64 which was seen very clearly in Fig 1a. The reduction in signal amplitude at long ranges is partly due to attenuation caused by material damping and scattering from rough surfaces, but is generally largely a result of the amplitude loss due to reflections from successive welds and other features. The usable range is therefore a function both of the attenuation, which is affected by the general roughness of the pipe surface and by some lossy coatings such as bituminous paint, and also the number of features along the pipe. The signals from the region around PS63 in Fig 2a are probably too small for defects to be detected reliably. However, this area was satisfactorily inspected from the location of Fig 1 in the backward direction (see Fig 1b).

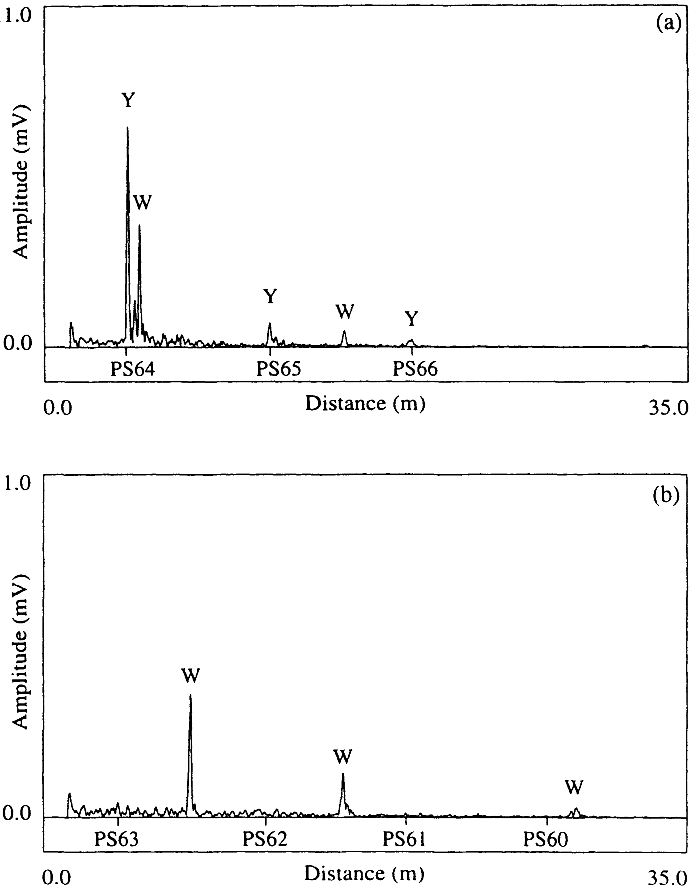

Figure 1. Received signals from one transducer location. (a) forward direction; (b) backward direction.

The first small reflection marked C in Fig 2b was not identified as a defect at the time of the test but subsequent visual inspection revealed a small area of wastage of maximum depth about 1 mm (14% of the wall thickness) extending over about 25% of the pipe circumference and 400 mm along the pipe. There is then a set of echoes from the region of support PS59 which is similar to that from PS60 in Fig 2a. This region was not identified as defective at the time of the test, but the subsequent visual inspection revealed a region of corrosion similar to that around PS60. With more experience, these characteristic signals will be identified more reliably. The next signal seen in the plot is from a weld and this is followed by a series of small echoes from support PS58. The visual inspection revealed that there was corrosion here similar to that seen at PS59 and PS60. It is clear that at longer ranges, particularly after pipe features such as welds, it becomes more difficult to detect shallow defects. There was no significant reflection from the next two pipe supports and a second weld was identified roughly midway between them.

Fig 3 shows the results of a test at the location where the most severe corrosion was encountered. The three signals marked C1, C2 and C3 at the start of the trace were identified as likely corrosion sites. The later visual inspection revealed that these locations corresponded to deep pits up to 4 mm deep (57% of the wall thickness) in a generally

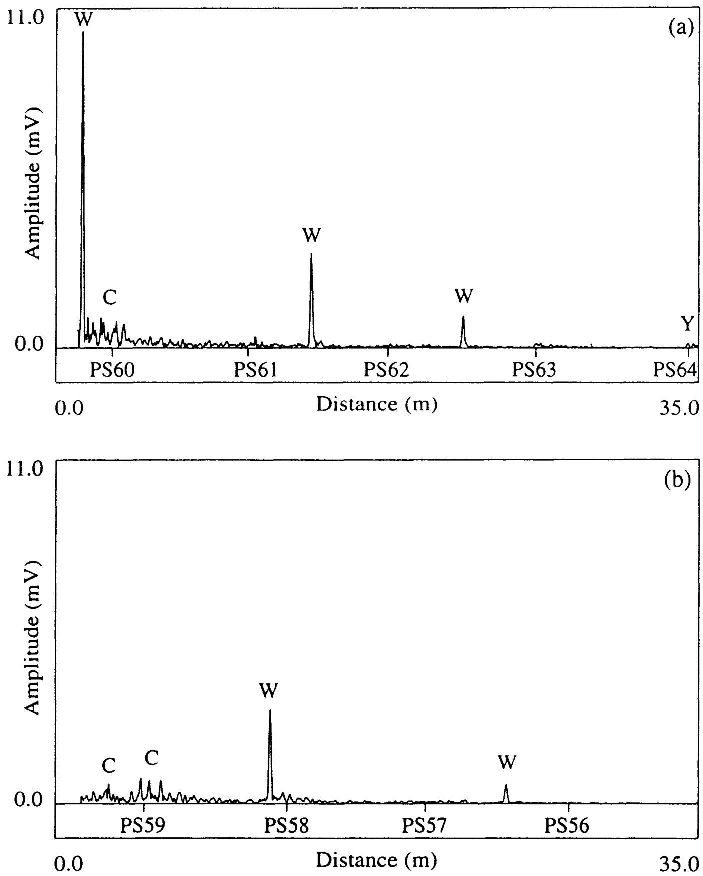

Figure 2. Results at location adjacent to that of Figure 1. (a) forward direction; (b) backward direction.

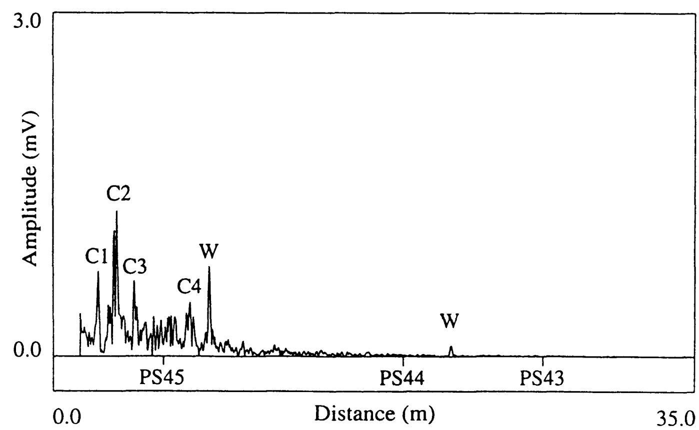

Figure 3. Result at location with most severe corrosion.

corroded area about 2m long extending over 30% of the pipe circumference. The full scale amplitude in Fig 3 has been reduced to 3 mV compared with 11 mV in Figs 1 and 2. This suggests that there was also a considerable amount of attenuation produced by scattering from the rough corroded surfaces. The location marked C4 was not originally identified as a corrosion site since it was thought that the signal could be caused by reverberation between the previously identified features. However, the visual inspection revealed a further area of corrosion covering about 25% of the pipe circumference with some pits extending to between 4 and 5 mm deep. This indicates that the reliable detection of defects downstream of large defective areas is likely to be difficult. This would not be a problem in practice since once the first region had been identified, the insulation would be removed from regions on either side in order to check the extent of the problem.

Tests were carried out at 13 locations on the pipe and the defect detection results are summarised in Fig 4. The depth data must be treated with some caution since it was obtained from rough measurements on site; there was no opportunity to produce replica mouldings. The horizontal and vertical lines on the plot correspond to the detection target of 16% (D/2) circumferential extent and 50% depth. All but one of the defects shown in Fig 4 whose circumferential extent exceeded 16% corresponded to clear echoes in the ultrasonic data, the exception being a defect 43% of the wall thickness deep extending over 25% of the circumference which was located 17.5 m from the nearest transducer position. The results suggest that on this pipe the reliable range is around 12-15m in either direction from a transducer location so successive test positions can be up to about 25-30m apart. The only defect whose depth was greater than 50% of the wall thickness which was not identified at the time of the test was corrosion site C4 of Fig 2b which was downstream of three other severe corrosion sites, C1-C3. The visual inspection also identified a further 18 corrosion sites which were not measured sufficiently accurately to be plotted on Fig 4. However, none of them had a depth greater than 50% of the wall thickness and most of them corresponded to minor wastage.

In addition to the correct corrosion identifications (marked + on Fig 4) four locations were incorrectly identified as defective at the time of the tests. Three of these came from the first transducer position at which blind tests were conducted. Subsequent investigations revealed that these false calls were due to echoes caused by reverberations between welds, or to mode conversion to the L(0,1) mode which the transducer system does not completely suppress on reception. In the later tests these possibilities were accounted for and false calls were avoided.

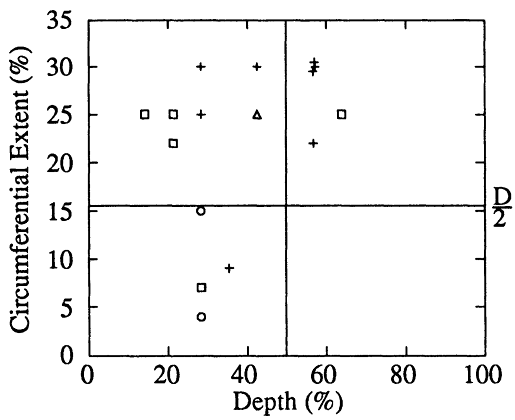

Figure 4. Summary of defect detection results. (+ corrosion identified correctly at time of ultrasonic tests; □ corrosion not identified at time of ultrasonic test, but subsequently correlated with distinct echo; o no correlation with ultrasonic echo; Δ no correlation with ultrasonic echo, but defect 17.5m from nearest transducer position.)

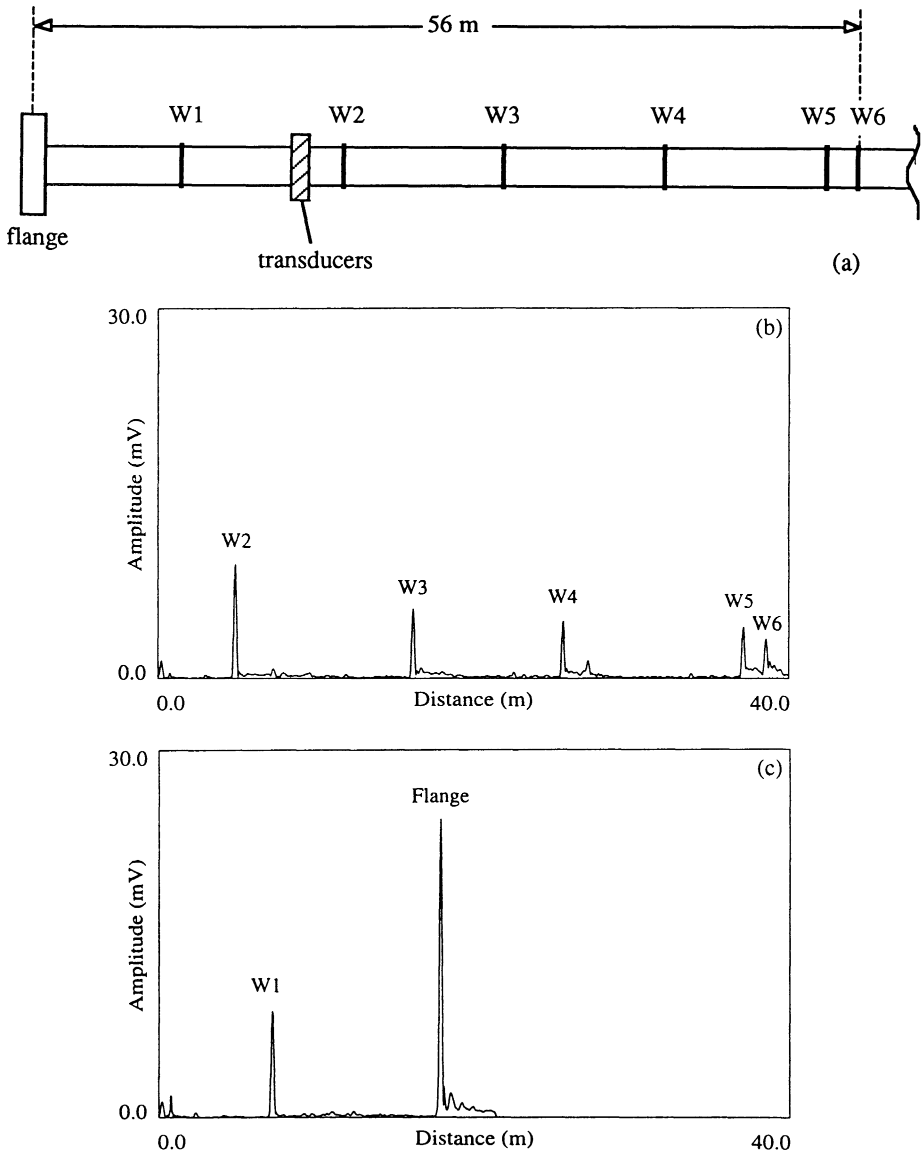

Figure 5. Results on 3 inch diameter schedule 40 pipe in better overall condition than the pipe of Figures 1-3. (a) schematic; (b) testing away from flange; (b) testing towards flange.

During the tests, 45 echoes were correctly identified as coming from welds with no "false calls". The amplitude of the reflections from welds was about 20% of the signal amplitude incident to them. The weld echoes were in general found to be an order of magnitude larger than echoes from other standard pipeline features, making them easy to identify during site testing. The welds occurred at regular intervals of about 13m, corresponding to the length in which the pipe was supplied.

CONCLUSIONS

The results show that the low frequency Lamb wave method can be used to detect corrosion under insulation in pipes and indicate that the target of detecting all sites where the wall loss is greater than 50% and the corrosion extends over more than 16% (D/2) of the pipe circumference will be achieved. The pipe tested here was in generally poor condition and the usable test range from each transducer position was about 12-15m in each direction, implying that successive transducer positions should be a maximum of 30m apart. On pipes whose general condition is better, much greater ranges can be achieved. For example, Fig 5a shows a schematic diagram of a section of a 3 inch diameter, schedule 40 pipe (wall thickness 5.5 mm) at another site. Figs 5b and 5c show the received signals in the directions away from and towards the flange respectively. A range of 40m is comfortably achieved in the direction away from the flange. Very little energy propagates across the flange, so this limits the range in the other direction, and the signal has not been plotted beyond the range of the flange in Fig 5c.

The axial resolution obtained using a 5 cycle, 64kHz tone burst was about 200mm and welds, defects and other features were located to within about 100mm using predictions of Lamb wave velocity based on standard tabulated properties of steel. Four "false calls" for corrosion were made at the time of the tests, three of these coming from the first transducer position at which blind tests were conducted. These were due to echoes caused by reverberations between welds, or to mode conversion to the L(0,1) mode which the transducer system does not completely suppress on reception. Software is now being developed to predict the arrival times of all reverberant echoes so that this problem can reliably be avoided.

General corrosion associated with a gradual loss of the wall thickness over a significant length of pipe did not produce significant echoes. However, echoes from severe localised wastage or deep pits within the generally corroded areas were detected. These areas of severe wall loss are particularly important to detect and they are frequently surrounded by generally corroded regions which may be within the corrosion allowance. It is therefore encouraging that the severe pits can be detected separately from the generalised corrosion. Little site work has so far been done on corrosion at features which are themselves significant reflectors. It is encouraging that defects removing only about 25% or less of the wall thickness in the region of the welded 'Tee' pipe supports were correctly identified in these tests, but a 'good' support of this type is not a large reflector. It would be much more difficult to identify corrosion around the welded yoke supports or at the girth welds. The measurement of mode converted signals may be a significant help in this area [8].

The results of these first "blind" site trials are very encouraging and suggest that the technique can be further developed to detect corrosion and other pipeline defects very efficiently with a minimum of false calls.

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